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13. ABSTRACT *(Maximum 200 words)*

This report discusses the results of applying distributed sensing & cooperative control algorithms to the problem of chemical plume localization. The algorithms were found to work well provided the plume as a function of (x,y) is dense.

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FINAL REPORT

GRANT #: N00014-99-F-0086

PRINCIPAL INVESTIGATOR: Dr. John E. Hurtado

INSTITUTION: Sandia National Laboratories, Albuquerque, NM

GRANT TITLE: Distributed Sensing and Cooperative Control for Plume Tracing

AWARD PERIOD: 11 Mar 99 to 01 Jan 00

OBJECTIVE: The objective of this proposed research was to apply distributed sensing and cooperative control algorithms developed by Sandia researchers (under separate DOE contracts) to the problem of chemical plume localization.

APPROACH: The distributed sensing and cooperative control algorithms were tested against mathematically modeled simulated plumes and against real plume data.

Two simulated plumes were considered. The first was given by the expression

Simulated Plume 1: $F(r,\theta,t) = -\exp(-2r^2)(\cos(\pi+20r+5\theta-t)-4)$

This function swirls with time and the nominal maximum value is at $(r,s)=(0,0)$. The second was given by the expression

Simulated Plume 2: $F(r,\theta,t) = -\exp(-2r^2)(\cos(10r-4t)\cos(5\theta-4t) + 4)$

This function appears like a swirling flower pattern. These functions result in plumes that are dense.

The algorithm was tested against real plume data provided by the ONR via other researchers under this sponsored program. The real plume data differed significantly from the simulated plumes in that the real data is very sparse.

ACCOMPLISHMENTS: The algorithm for plume localization relies on distributed sensing and communication. Each robot of a team uses sensors to sample the plume field at its current location. This robot location and sensor reading information is transmitted to other robots of the team. Each robot uses this information to determine a position update (a current control) that brings it closer to the unknown plume source. This method provides a decentralized approach in plume localization because each robot determines its own update strategy. The mathematical details of this approach are explained in the Sandia Report SAND2000-3110.

The algorithm was tested against two simulated plumes. The first plume is given by

Simulated Plume 1: $F(r,\theta,t) = -\exp(-2r^2)(\cos(\pi+20r+5\theta-t)-4)$

This function swirls with time and the nominal maximum value is at
$(r,s)=(0,0)$. The function folds softly sway form the origin but
sharply near the origin. The function is shown in Figure 1a, and
Figure 1b shows robot movement for a team of 16 cooperating robots.
The figure shows position updates 1 through 3. The robots are
initially in the lower left region, and movement is denoted from 'x' to
'o'. The robots sense the chemical plume and they immediately begin
towards the origin. Figure 1c shows robot movement for position
updates 7 through 9. Notice that the leading robots actually overrun
the target. Figure 1d shows robot movement for position updates 16
through 18. The robots have found the target and remain in the vicinity
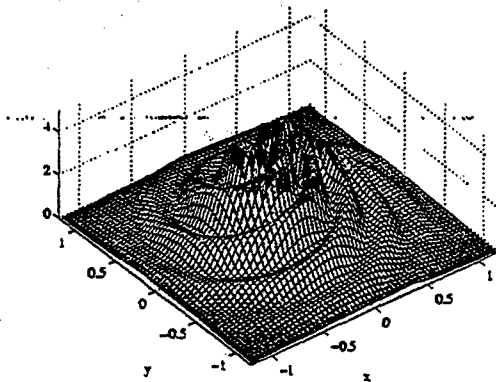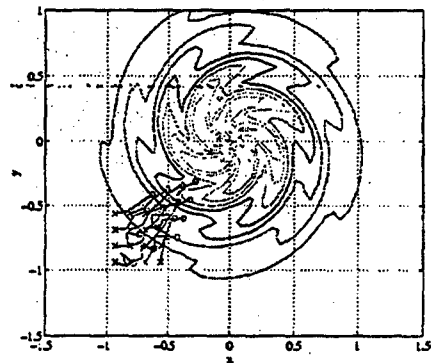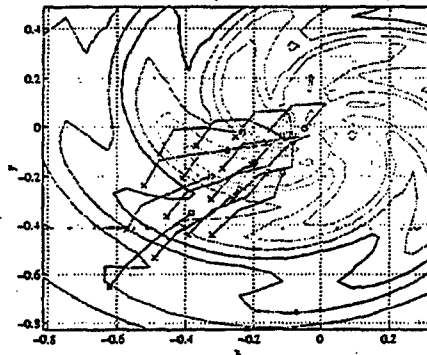of the origin.

Figure 1a
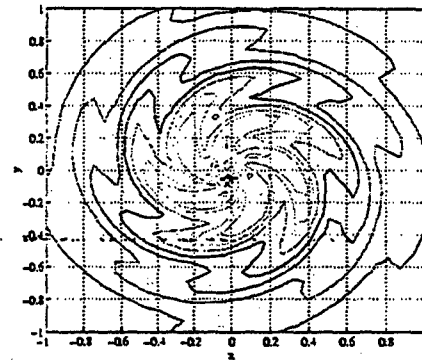
Figure 1b

Figure 1c

Figure 1d

Figures 1a through 1d. The position updates of a team of 16 robots
cooperating to localize Simulated Plume 1.

The other simulated plume is given by

Simulated Plume 2: $F(r,\theta,t) = -\exp(-2r^2)(\cos(10r-4t)\cos(5\theta-4t) + 4)$

The robots were able to localize the source of this simulated plume
also.

The algorithm was tested against real plume data provided by the ONR
via other researchers under this sponsored program. The real plume
data differed significantly from the simulated plume in that the data

is very sparse. A one-frame snapshot of plume data is shown in Figure
2a, and a time average (over hundreds of frames) is shown in Figure 2b.
A team of robots was using the distributed sensing and cooperative
control algorithm was able to localize the source provided the robots
averaged their sensor readings over many collected samples (i.e.,
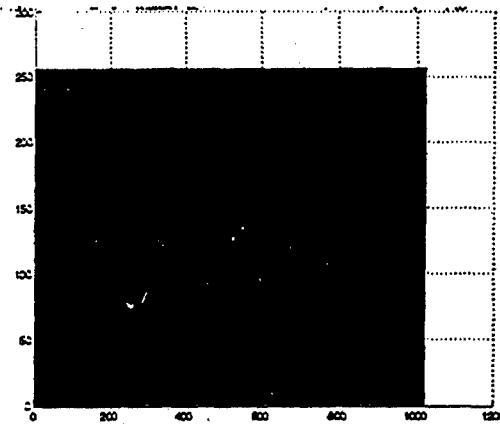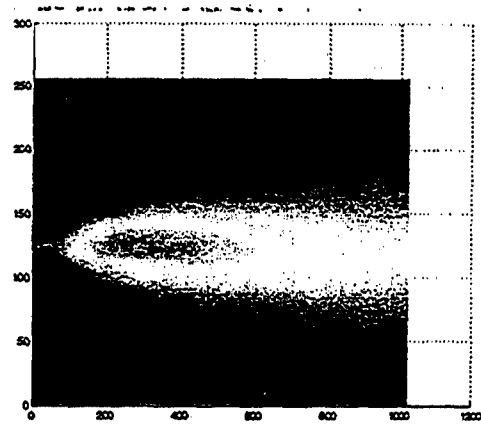hundreds of frames of data).

Figure 2a   **Figure 2b**

Figures 2a and 2b. The real plume data. A single frame of data (2a)
and a time average (over hundreds of frames) (2b).

CONCLUSIONS: We were able to successfully apply our distributed
sensing and cooperative control algorithms to the problem of chemical
plume localization. The method works well provided the plume as a
function of (x,y) is dense. If the plume is sparse across the space
(x,y), then it was necessary for the robots to average their sensor
readings over many collected samples. The reason is that the algorithm
operates on a model of the plume, which requires the plume to have a
definite structure. For the simulated plumes this structure is
present. For the real plume data, this structure is not present in a
single frame of data, but does begin to form when many frames are
averaged together.

SIGNIFICANCE: Our studies have demonstrated that our decentralized
cooperative control method can be used to perform autonomous source
localization of chemical plume sources.

PATENT INFORMATION: The United States government has granted a patent
for a hardware robotic testbed that executes the cooperative source
localization method that Sandia has developed and applied to the plume
problems discussed in this report. Patent number US 6,408 226B1,
"Cooperative System and Method Using Mobile Robots for testing a
Cooperative Search Controller."

AWARD INFORMATION: None.

PUBLICATIONS (for total period of grant): None.